# The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect

R.F. Follett • J.M. Kimble • R. Lal

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# CHAPTER 12

# The Effects of Pasture Management Practices

*R.R. Schnabel,[1] A.J. Franzluebbers,[2] W.L. Stout,[3] M.A. Sanderson,[4] and J.A. Stuedemann[5]*

## Introduction

Pastureland, which includes improved, native, and naturalized pastures, accounts for 51 Mha of the 212 Mha of privately held grazing land in the U.S. (Sobecki et al., Ch. 2). This chapter focuses on improved pasture in humid regions (>625 mm mean annual precipitation).

*Improved pasture* is grazing land permanently producing indigenous or introduced forage species, harvested primarily by grazing, and managed to enhance forage quality and yield. Livestock raised on these lands can be grazed, confined and fed stored forages, or both.

### Geographic regions and their forages

Grazing lands vary widely within and among the three major geographic regions of the eastern U.S. (Fig. 12.1). Washko (1974) divided the $5^1/_4$ Mha of pastureland in the 12 *northeastern states* (10% of the total area) into four classes: cropland pastures, improved pasture, woodland pasture, and other. The improved permanent pastures we focus on are predominantly Kentucky bluegrass (*Poa pratensis* L.)/wild white clover swards containing an indeterminate mixture of orchardgrass (*Dactylis glomerata* L.), timothy (*Phleum pratense* L.), and quackgrass (*Agropyron repens* L. Beauv.) (Rohweder and Albrecht, 1994). These pastures have been im-

[1] Soil Scientist (Deceased), Agricultural Research Service, University Park, PA.
[2] Ecologist, USDA/ARS, Watkinsville, GA, (706) 769-5631 X223, afranz@arches.uga.edu.
[3] Soil Scientist, USDA/ARS, University Park, PA, (814) 863-0947, ws1@psu.edu.
[4] Research Agronomist, USDA/ARS, University Park, PA, (814) 865-1067, mas44@psu.edu.
[5] Research Animal Scientist, USDA/ARS Watkinsville, GA,(706) 769-5631 X247, jstuedem@arches.uga.edu.

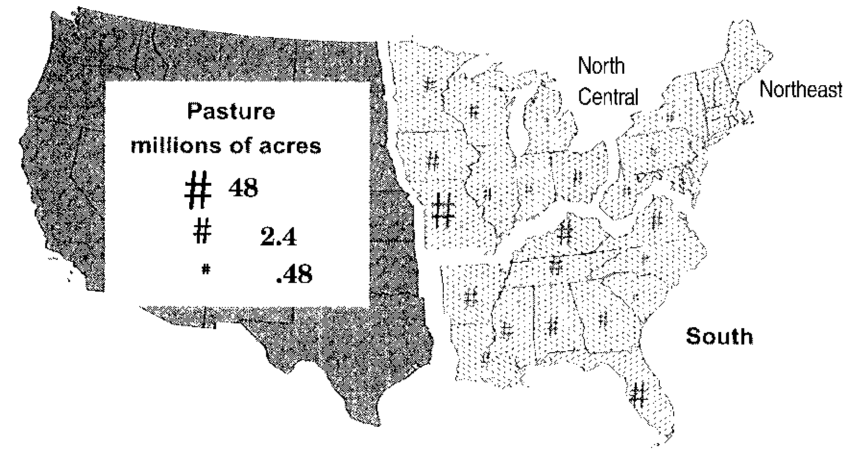



**Figure 12.1. Grazing lands in the eastern U.S., 1987. Grazing land is the sum of permanent pasture, cropland, and woodland used only for grazing. Data are from Vough (1990).**

tures have been improved by adding lime and fertilizer and renovating (sod/seeding legumes or grasses).

Grazing lands in the *North Central* geographic region occupy about 9 Mha. Forage species are similar to those in the northeast, except that tall fescue (*Festuca arundinacea* Schreb.) predominates in the southern reaches and smooth bromegrass is common in the northern and central portions.

In the *humid South*, pasture and forage species shift from cool season species typical of the transition zone (e.g., tall fescue, orchardgrass, red clover) to predominantly warm season species such as bermudagrass (*Cynodon dactylon*), bahiagrass (*Paspalum notatum*), and dallisgrass (*Paspalum dilatatum* Poir.) farther south. Cool season annual forages such as annual ryegrass, small grains, and several clovers (arrowleaf, crimson, subterranean, and white clover) frequently are planted as winter annual pastures on prepared seedbeds or sod/seeded into dormant warm season grass sods.

## Grazed and stored forage

We consider pastures and grasslands since, even when livestock get most of their nutrients by grazing, the most efficient forage-based animal agriculture requires both grazed pastures and conserved forage. In temperate climates, pastures partially or entirely support animals for as little as 5 months to as much as the entire year. The rest of the year, pasture plants grow little or are dormant, and animals get their nutrition from conserved forages.

Stored forages are also necessary given the growth habits of temperate grasses and legumes. Common cool season forages produce less forage during the warmer months of the year (July-August) than during the spring and cool months of fall. Producers commonly stock pastures for the forage produced during July-August, which leaves more forage than grazing animals can consume during the rest of the growing season. The producer harvests excess forage and feeds it later. The periods of slow growth occur at different times and for different lengths of time in all climatic regions, but they occur, and managers must account for them.

## Soil organic carbon research

Soil organic C (SOC) status and changes in response to crop management have been the subject of much research and the topic of numerous reviews and book chapters (Kononova, 1961; Tate, 1987; Jenkinson, 1988; Scow, 1997; Burke et al., 1997; Follett et al., 1995). However, relatively little of this research specifically has addressed pasture management in the U.S.

The governing principles are similar for pastures and cropland. The balance between rates of organic C (OC) input and decomposition, expressed over time, accounts for the current level of soil C in pastures. Whether pastures will sequester C in response to management or climatic perturbations depends on the relative change in these two processes. Plant, climate, animal, and soil properties control pasture productivity and OC decomposition. Most factors that change net primary productivity (NPP) also change rates of decomposition. It is reasonable to assume that conditions that encourage biomass production also maximize OC decomposition (Tate, 1987).

The majority of improved pastures in the U.S. are east of the Missouri River. They exist across a wide climatic range, from Vermont to Florida, and a broad range of precipitation amounts and distributions (Fig. 12.1). Pastures are on many soil types with varying fertility, texture, and structure. The climatic factors and soil properties have profound, generally predictable effects on SOC. Complex interactions among these variables, which are not fully understood, also may affect SOC.

## Temperature, moisture, and net primary productivity

Overall, temperature and moisture are the most important climatic factors determining C flow in soils. Both factors affect NPP and microbial activity similarly. Rates of both forage production and OC decomposition are highest at temperatures of 25 to 35°C and soil moisture contents of 50 to 80% water-filled pore space, and they decline as either temperature or moisture content increase or decrease from these optimal ranges. Reductions in temperature slow decomposition more than they reduce forage production (Burke et al., 1997). Soil water status strongly influences microbial activity. If the soil is too dry, activity nearly stops, and if the soil is too wet, decomposition slows and becomes less complete.

As long as NPP is sufficient, the greatest amounts of SOC accumulation occur in cold climates or in soils that are saturated a large portion of the year (Scow, 1997). Sorption to clay, isolation in micropores, and physical protection within stable macroaggregates reduce organic matter (OM) availability (Scow, 1997). Consequently, rates of decomposition are expected to be higher in coarsely textured soils and poorly structured soils, especially those with few stable macroaggregates.

### Types of management strategies

Pastureland management strategies can influence SOC. They can be strategies to manage animals, plants, and soil. Managing these variables can change relative rates of C inputs and outputs, which control steady-state levels of SOC within a climatic region on a specific soil type. SOC sequestration is generally greatest shortly after a change in management and then diminishes as rates of C input and SOC decomposition balance each other over the long term.

## Effects of Animal Management

Relatively little literature deals directly with the impact of specific grazing management practices on SOC. Milchunas and Lauenroth (1993) compiled a worldwide data set of 236 grazing studies that compared one or more attributes of grazed and ungrazed sites. Nearly all of the 236 sites were rangeland that received less precipitation and fewer amendments and were far less productive than pastureland in the eastern U.S. Most studies focused on aboveground NPP. The reviewers concluded that grazing reduced aboveground NPP.

In natural ecosystems of perennial plants, annual biomass production below ground generally exceeds that above ground. Root mass was greater at grazed sites in 2/3 of the studies with measurements, and, when production was viewed at the whole plant level, grazing had no effect on plant production (Milchunas and Lauenroth, 1993). SOC or OM was measured at only 37 of the sites. No difference in SOC was found between grazed and ungrazed rangelands in which no biomass was removed from ungrazed sites. Unless stated otherwise, manure was only for grazing treatments. Ungrazed, unharvested, or mechanically harvested treatments did not receive manure.

## Grazing vs. haying

In animal production systems, biomass is removed from pasture either by grazing or by mechanical harvesting, which is most commonly haying. A direct relationship exists between the level of SOC and annual additions of C to soil via crop residues (Paustian et al., 1995). Consequently, the rate of increase in SOC is higher under grazing than when hay is removed, because greater amounts of C are returned to the soil. Grazing returns 60% to 95% of ingested nutrients to the pasture as excreta (Till and Kennedy, 1981). In addition, stubble production with grazing can be up to 5% greater than with mechanical harvest (van den Pol-van Dasselaar and Lantinga, 1995; Dyer et al., 1998).

During the first 3 years of steer grazing on Coastal bermudagrass, SOC increased at a rate of 1.5 to 1.8 MT/ha/yr on Cecil-Madison-Pacolet-dominated sandy loams to sandy clay loams (clayey, kaolinitic, thermic Typic Kanhapludults) (Lovell et al., 1997). SOC under bermudagrass, that was harvested as hay or left unharvested for conservation, increased at a rate of only 0.3 to 0.4 MT/ha/yr. The similar, relatively low soil C accretion rates in unharvested and hayed management systems occurred because much of the aboveground, plant-derived C was not incorporated into the soil with either management. The higher rates of soil C accretion under cattle grazing were due to the return to the soil of much of the plant-derived C as feces that quickly became part of the SOC pool.

Following 15 to 19 years of cattle grazing on Tifton 44 or Coastal bermudagrass, SOC to a depth of 20 cm averaged 36.7 MT/ha, while three paired hayed fields contained 31.1 MT SOC/ ha (Franzluebbers et al., 2000b). Most of the difference in SOC between grazed and hayed bermudagrass occurred in the surface 5 cm (Fig. 12.2). C in surface residue was also greater under grazed (1.8 MT/ha) than under hayed (1.2 MT/ha) bermudagrass.

Hassink and Neetson (1991) in a 3-year study measured 2.4 MT/ha/yr more residues returned to the system with grazing than with mowing. SOC averaged 8.9 MT/ha more in the top 25 cm in grazed pastures than in mowed grassland, with little response to fertilizer rates from 250 to 700 MT N/ha/yr. In a later study, Hassink (1994) found the effect on SOC of grazing compared to mowing to be small and inconsistent.

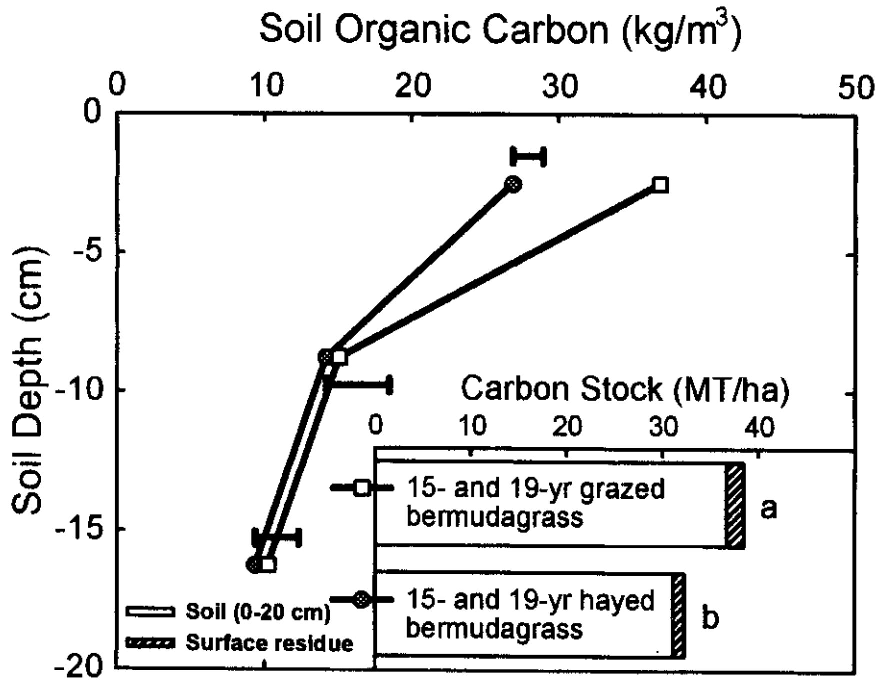



**Figure 12.2. SOC depth distribution and standing stock to a depth of 20 cm under grazed and hayed bermudagrass management on a Typic Kanhapludult in Georgia (Franzluebbers et al., 2000b). LSD bars are P = 0.05 within a soil depth. Horizontal bars followed by a different letter are different at P = 0.05.**

## Stocking methods

The method of stocking pastures also may influence SOC. The addition of fertilizer and lime and the use of improved species make intensively managed pastures more productive. Where moisture does not constrain yield, levels of NPP are greater with intensive rotational grazing than intensive continuous grazing.

Pastures stocked continuously with few animals are least productive. For example, during the first 3 years of cattle grazing on Coastal bermudagrass, SOC increased significantly at a rate of 2.7 kg/ha for each additional grazing day within the range of 600 to 1200 grazing days/ha/yr (Stuedemann et al., 1998). The heavier foot traffic associated with the generally higher stocking densities used with more intensive vs. less intensive grazing practices may enhance breakdown of aboveground litter and its incorporation into the soil (Schuman et al., 1999). In contrast, where a moisture deficit limits production, as in western rangelands, intensive grazing may damage the stand with a concomitant loss of SOC (Hoglund, 1985; Dormaar and Willms, 1998).

## Redistribution of nutrients

Spatial redistribution of plant residue and excreta from foraging areas to areas where animals congregate (camping areas) can alter SOC distribution and quantity. In six pastures on the south island of New Zealand, the difference in SOC between the main grazing areas and camping areas was significant and ranged from 3 to 14 g/kg (Haynes and Williams, 1999).

In Georgia on a Typic Kanhapludult, SOC also was concentrated most near permanent shade and water sources (i.e., camping area) in 7- to 15-year-old tall fescue pastures (Fig. 12.3). Although some literature exists on redistribution of a few different nutrients in pastures (Follett and Wilkinson, 1995; Haynes and Williams, 1999; Wilkinson et al., 1989; West et al., 1989; Peterson and Gerrish, 1996), much more research is needed to understand SOC redistribution caused by grazing and its influence on C sequestration.

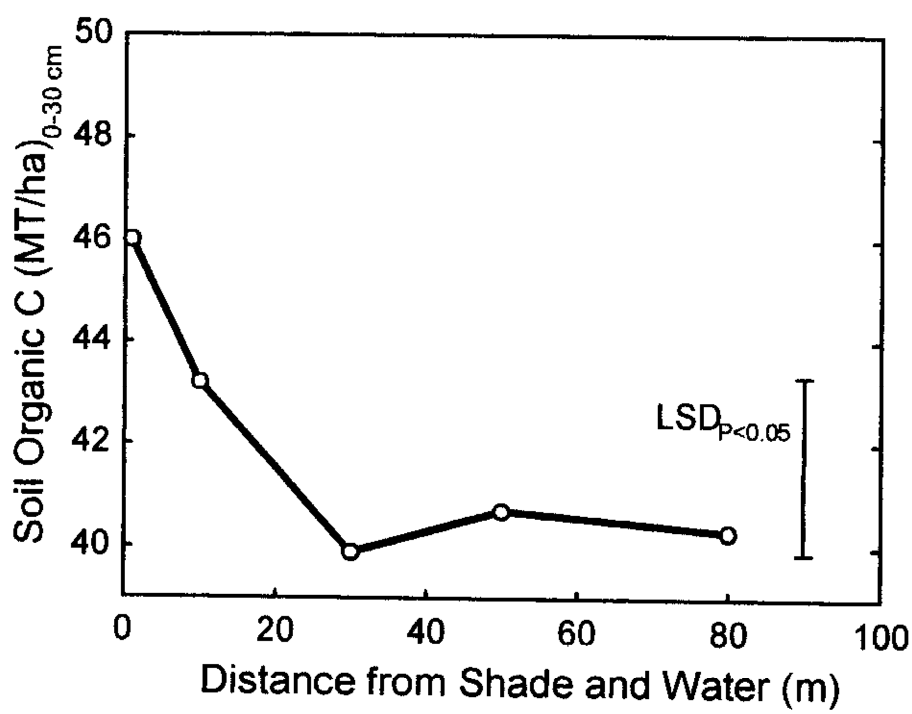



**Figure 12.3. SOC redistribution within tall fescue pastures on a Typic Kanhapludult in Georgia (Franzluebbers et al., 2000a).**

## Effects of Forage Management

Forage and soil management obviously have interacting effects on C sequestration in grazing lands. A key to increasing C storage is increasing pasture productivity. We can either accept site conditions and select productive vegetation more suited to the site, or we can change site conditions by fertilizing, liming, or draining to improve pasture production.

Changes in site conditions often change the vegetative mix. Liming and adding P favors legumes. Adding N makes cool season grasses more competitive and reduces the quantity of legumes and warm season grasses. Likewise, we may need to alter site conditions to create an environment in which introduced species can become established. Although sections of this chapter address forage and soil management separately, interactions are apparent.

Animal-based agriculture in the humid eastern U.S. always has required managing vegetation. Clearing forests and planting nonnative grasses and legumes created much of the highly productive pastureland in the humid temperate regions of the world (Tothill, 1978). The continued existence of those pastures depends on management practices, such as grazing frequency and intensity, lime and fertilizer inputs, and occasional replanting (Haynes and Williams, 1993). Thus, the typical temperate, cool season grasses in these pastures (e.g., Poa, Dactylis, Festuca, Lolium) do well where rainfall and soil fertility are favorable (Haynes, 1980).

While management is necessary to maintain productive eastern pastures, the effect of forage management on soil C has not been an area of active research. This section qualitatively estimates forage management's effects on soil C through its impact on forage yield and quality — where *yield* is a surrogate for NPP, and *quality* is a surrogate for microbial decomposition. To sequester C, grasses should increase OC input to the soil, but, for the C to remain in the soil, it should decompose slowly, with the overall effect that input exceeds decomposition.

### Yield and carbon sequestration

Grass yields vary considerably across gradients in moisture and fertility. Moisture deficits and low fertility generally favor warm season grasses (Stout, 1992; Stout and Jung, 1992, 1995). When no or moderate amounts of N were applied, warm season ($C_4$) grasses consistently produced more biomass than cool season ($C_3$) grasses in Pennsylvania hill lands (Table 12.1).

Yields of all grasses increased in response to N fertilization. Yield differences between grass types and among species within a type were smaller at the higher fertility level. At optimum moisture and fertility, all grass types are highly productive (Table 12.2).

From these yield patterns, we infer that, at low to moderate fertility, more C is stored under warm season grasses, and the difference between warm and cool season grasses decreases as fertility increases. Wedin and Tilman (1996) reported this pattern of C storage for grasslands in Minnesota.

**Table 12.1. Mean yields (MT/ha) of warm and cool season grasses in Pennsylvania.**

| Grass | W/O Fertilizer | 75 kg N/ha/yr |
|---|---|---|
| **Warm season grasses** | | |
| Niagara big bluestem | 4.4 | 6.8 |
| Blackwell switchgrass | 4.2 | 7.9 |
| NJ50 switchgrass | 10.7 | 11.2 |
| NY591 indiangrass | 5.2 | 6.2 |
| **Cool season grasses** | | |
| KY31 tall fescue | 0.8 | 3.8 |
| Reed canarygrass | 1.6 | 3.9 |
| Pennlate orchardgrass | 1.3 | 3.1 |

Much of the increase in SOC in tall grass and mixed grass prairies in recent years comes from a shift in species composition to greater proportions of warm season grasses (Schuman et al., Ch. 11). Warm season grasses generally have higher root/shoot ratios, more root biomass, and greater belowground C than cool season grasses. Also, many of the mixed and short grass warm season species are more shallowly rooted.

**Table 12.2. Mean yields (1989-1991) from cool season grasses in Pennsylvania.**

| Grass | Yield (MT/ha) |
|---|---|
| Orchard grass | 11.5 |
| Perennial rye grass | 8.9 |
| Reed canary grass | 10.1 |
| Brome grass | 9.5 |
| Tall fescue | 13.7 |
| Timothy | 10.9 |

*Grasses were fertilized with 225-275 kg N/ha.*

At low to moderate levels of N added to a Minnesota prairie soil, Wedin and Tilman (1996) reported significantly more C storage under warm season grasses than under cool season grasses. Increasing levels of N additions, however, caused a shift from grasslands dominated by highly diverse warm season grass to grasslands dominated by cool season grasses low in diversity. Therefore, given the high levels of N commonly applied, either as fertilizer, manure, or legumes, it may not be possible to shift from cool to warm season grasses to sequester C in many eastern pastures.

## Quality and carbon sequestration

Forage quality is defined in terms of the relative performance of animals when fed herbage on a nonlimiting basis. Forage quality is a function of the nutrient concentration of the herbage, its rate of intake by the animal, digestibility of the material eaten, and the efficiency with which the animal uses the metabolized products (Buxton and Mertens, 1995). Forage quality reflects the environment in which the plant was grown (including climatic, edaphic) and genetic factors.

Grass and legume species vary in forage quality, as do cultivars within species. Examples of warm season forage grasses bred for improved forage quality are 'Coastal' bermudagrass and 'Trailblazer' switchgrass, both of which were selected for improved digestibility of dry matter (Burton, 1989). A high quality forage, one that ruminants readily digest, is a forage that soil microorganisms also decompose more readily.

Many factors affect forage quality, but the overwhelming factor, and the one over which a producer has the most control, is plant maturity. All forage plants are higher in quality when young than when mature (Figs. 12.4a, 12.4b). The decrease in quality with maturity results from changes in plant morphology (Fig. 12.5) and from compositional and anatomical changes in plant tissues. As the plant matures, both cell wall concentrations and lignification typically increase, which reduces digestibility. Young plants usually contain a greater concentration

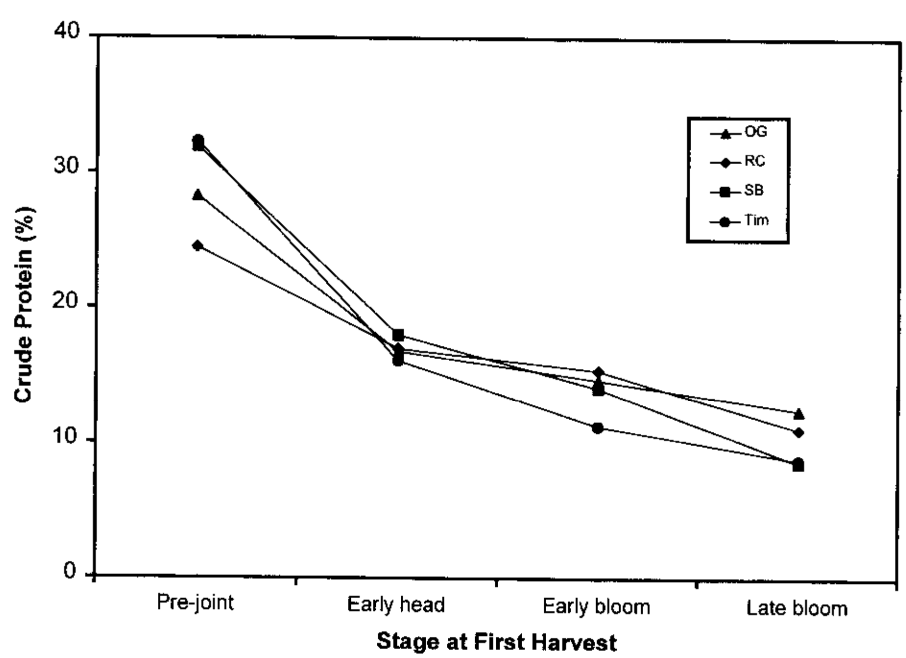



**Figure 12.4a. Crude protein concentration of common pasture grasses at different developmental stages. Adapted from NE Reg. Pub. 550, 554, 557, and 570, Management and Productivity of Perennial Grasses in the Northeast, West Virginia Agricultural Experiment Station. (OG = orchard grass; RC = red clover; SB = smooth brome grass; Tim = timothy.)**

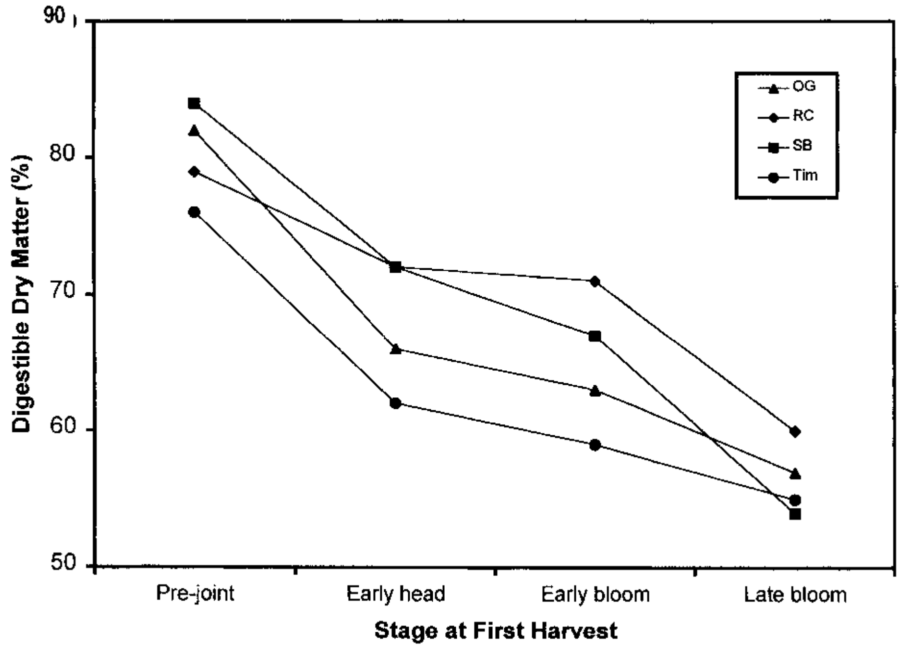



**Figure 12.4b. Digestible dry matter concentration of common pasture grasses at different developmental stages. Adapted from NE Reg. Pub. 550, 554, 557, and 570, Management and Productivity of Perennial Grasses in the Northeast, West Virginia Agricultural Experiment Station. (OG = orchard grass; RC = red clover; SB = smooth brome grass; Tim = timothy.)**

of N, resulting in higher protein concentration, lower C:N ratio, and greater degradability.

When grasses and legumes are harvested at the proper growth stage, legumes are usually higher in protein, and more digestible, but quality ranges widely within each group. As plants mature, they produce more biomass, but quality declines. Shorter days, higher temperatures, and lower available soil moisture cause quality losses in late summer, regardless of morphologic development. Delaying haying or grazing might increase SOC, but it does so at the expense of animal productivity.

Cool season grasses generally are of higher quality than warm season grasses, and annuals generally are of higher quality than perennials. However, forage quality also differs among cultivars of both warm and cool season grasses. For example, the switchgrass varieties *cave-in-rock* and *NJ50*, selected to provide animal feed, produce higher-quality forage than *shelter*, a variety selected more often for soil conservation purposes.

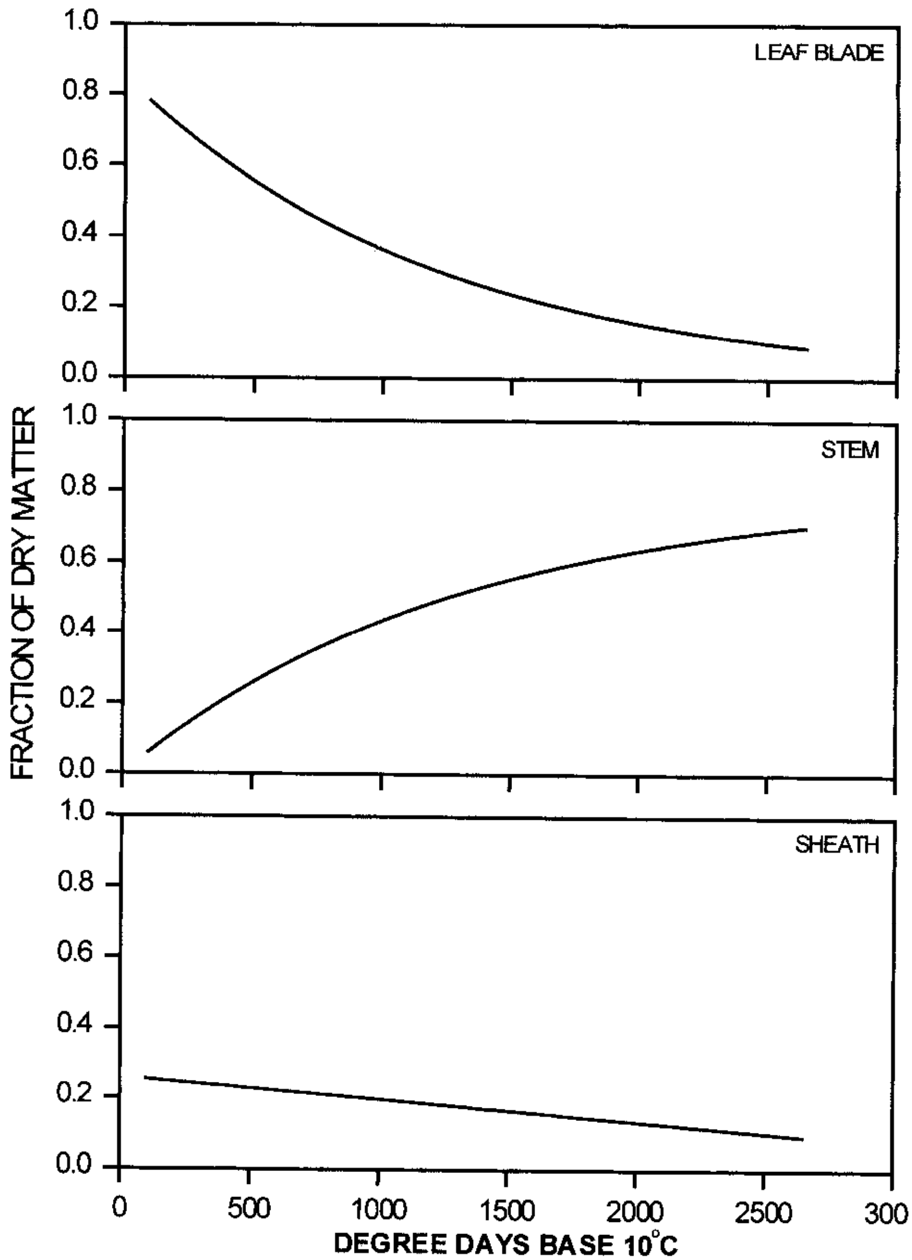



**Figure 12.5. Changes in plant morphology of a warm season grass. Equations taken from Sanderson and Wolf (1995a).**

Based on the forage quality patterns described above, we should be able to select grasses that decompose more slowly while maintaining relatively high levels of NPP. Managing eastern U.S. grazing lands to maximize store C storage, however, might result in suboptimum levels of animal production. Much more research is required to identify the management inputs needed to balance SOC storage with animal productivity.

The work of Franzluebbers et al. (1999b) provides an example of how grass management can affect SOC. Tall fescue is an important cool season perennial forage for many cattle producers in the humid regions of the U.S. and throughout the world. It is grown on more than 14 Mha of land in the U.S. (Buckner et al., 1979). The majority of tall fescue pastures in the U.S. is infected with a fungus, *Neotyphodium coenophialum* (Shelby and Dalrymple, 1987), which resides primarily within basal stem tissue. In Georgia, tall fescue with low endophyte infection (0% to 20%) had 29.1 MT SOC/ha in the upper 15 cm of soil, compared to 31.2 MT SOC/ha with high endophyte infection (60% to 100%) (Franzluebbers et al., 1999b). Lower potential soil microbial activity and a change in soil microbial community structure accompanied greater soil C sequestration with higher levels of endophyte infection. Biochemical alteration of the plant material caused by the endophyte may have directly or indirectly suppressed SOC decomposition.

We expect interactions among forage species and climate, forage species and grazing management, and soil management and forage quality, and ultimately all of these factors on SOC. Much of that information appears in the *NRCS National Range and Pasture Handbook* (NRCS, 1997). The end of this chapter summarizes the effects of forage management on SOC.

## Effects of Soil Management

Soil management affects SOC in pastures much as it does in cropland. Management that increases NPP more than it increases decomposition results in greater SOC. When soils with low inherent fertility (i.e., low SOC) are fertilized or limed, productivity and SOC generally increase. Phosphorus availability can limit productivity where legume/grass mixtures provide forage.

Crocker and Holford (1991) surveyed 67 pasture sites in the New South Wales tablelands of Australia with SOC ranging from 20 to 29 g/kg. Adding 125 kg P/ha as superphosphate over 15 to 45 years increased SOC by 2 to 3 g/kg, with the greatest increase on soils derived from granite.

In another study in Australia, a pasture that received 4.5 MT/ha of superphosphate and 11.25 MT/ha of lime over 73 years had 67 g SOC/MT compared to 4.9 g SOC/kg in a pasture receiving neither P fertilizer nor lime (Ridley et al., 1990). In a study in New Zealand, adding 188 kg P/ha as superphosphate over 37 years substantially increased SOC (Haynes and Williams, 1992). No further increases in SOC were reported for applications of 376 kg P/ha.

In plant communities with few legumes on low-fertility sites, N amendments often increase forage production and SOC. Ladd et al. (1994) reported a linear increase in SOC with additions of N up to 80 kg N/ha. SOC in this Australian study increased for treatments that returned more crop residue to the soil.

Similar results were obtained in Kansas where smooth bromegrass yields increased with N applications up to 67 kg/ha/yr (Schwab et al., 1990). SOM paralleled yields and increased from 38 to 48 g/kg after 40 years of fertilization. When N applications were discontinued in part of the smooth brome grass experiment after 20 years, no differences in SOC appeared between the 20 and 40-year fertilized plots at the end of the 40-year period.

In Alberta, Canada, Malhi et al. (1997) reported that SOC increased by 18.5 MT/ha after 27 years of 56 kg N/ha/yr on smooth brome grass and by 23.4 MT/ha at 112 kg N/ha/yr. SOC increased most with ammonium nitrate and least with urea as the N source.

At the end of 15 years of tall fescue management with cattle grazing in Georgia, SOC was 2.6 MT/ha greater under high than under low fertilizer application rates (Table 12.3). SOC differences between fertilizer application regimes resulted from significant differences at depths of 2.5 to 7.5 and 7.5 to 15 cm. About 2/3 of the change in SOC due to fertilization was due to accumulation of an intermediately decomposed pool of particulate OC. Interestingly, the fertilizer application regime did not lead to any differences in soil microbial biomass C, basal soil respi-

**Table 12.3. Effect of 15 years of fertilization of tall fescue pasture on SOC pools at Watkinsville, GA (Franzluebbers and Stuedemann, unpublished data). Low rate of fertilization was 134-15-56 kg N-P-K/ha/yr and high rate of fertilization was 336-37-139 kg N-P-K/ha /yr.**

| Soil Depth (cm) | Fertilization Rate | Soil Organic C (MT/ha) | Particulate Organic C (MT/ha) | Microbial Biomass C (kg/ha) | Basal Soil Respiration (kg/ha/d) |
|---|---|---|---|---|---|
| 0-2.5 | low | 10.2 | 5.1 | 822 | 24.1 |
| | high | 10.9 | 5.9 | 943 | 28.8 * |
| 2.5-7.5 | low | 11.0 | 4.1 | 585 | 15.0 |
| | high | 11.8 * | 4.6 * | 574 | 13.8 |
| 7.5-15 | low | 11.0 | 2.9 | 621 | 10.7 |
| | high | 11.7 * | 3.1 | 627 | 10.5 |
| 15-30 | low | 12.8 | 2.7 | 740 | 7.7 |
| | high | 13.1 | 3.6 | 897 | 7.2 |
| 0-30 | low | 45.0 | 15.0 | 2769 | 57.5 |
| | high | 47.6 * | 16.8 * | 3041 | 60.3 |

** Denotes significance at P = 0.05.*

ration, nor their ratios with particulate OC and SOC. Higher fertilizer application rates improved plant production, which probably led to more plant root and forage residues and animal feces to supply the particulate and total OC pools.

When soils that are inherently more fertile (i.e., higher in SOC) are fertilized, the affects on productivity and SOC are less certain. Yields may increase without a response in SOC. In the long-term experiment at Rothamsted, large inputs of inorganic fertilizers had little effect on SOC (Jenkinson, 1988). After 100 years of applying 20 MT manure/ha, or either 18 or 36 kg N/ha/yr, SOC ranged from 37 to 80 g/kg, with no clear pattern. Soil microbial biomass was highest with manure but was reduced significantly by adding NPK. Without manure, there was less soil microbial biomass, but it was more active as measured by microbial respiration.

The differences in microbial activity may reflect differences in the ratio of bacteria to fungi that would be supported in the soil at the prevailing pH of treatments (Hopkins and Shiel, 1996). Withholding P from a ryegrass/clover pasture in New Zealand, with ~7.5% SOC, affected yield but not nutrient cycling within the first 2 years (Perrott et al., 1992). SOC did not respond to 10 years of low level P and S additions in another New Zealand study (Ross et al., 1995) where SOC was ~7%.

In a fertilizer rate study in Kansas with N additions up to 224 kg/ha/yr (Owensby et al., 1969), smooth bromegrass yields were greatest with the highest N application. However, SOC did not increase with increasing N. The authors speculated that increased microbial activity at higher N rates, resulting in more rapid decomposition and C oxidation, negated the effects of greater productivity on SOC.

SOC was not affected significantly by supplying N to a Coastal bermudagrass pasture, either as broiler litter or inorganic fertilizer, for 3 years (Lovell et al., 1997). The warm, moist environment in northeast Georgia probably led to rapid decomposition of the ~2.2 MT/ha/yr of added C in broiler litter.

Fertilizer additions also may result in less SOC by reducing the amount of photosynthate directed to roots or by producing more biodegradable roots and shoots. Litter decomposition links with the C/N ratio of the biomass, and the added N may produce a more N-rich and hence more degradable forage. Poorly drained pastures at North Wyke, southern England, receiving 200 kg N/ha/yr for 50 years, had 110 g/kg less SOC in the upper 10 cm than pastures receiving no N (Lovell et al., 1995).

Reduced total, microbial, and mineralizable C pools in fertilized compared with unfertilized pastures were attributed to less root production at the expense of increased herbage production. Application of high rates of N leads to reductions in root mass and root C input to the soil (Ennick et al., 1980). The amount of root C contribution to the soil is often less than the increase in herbage returned to the soil following fertilization (Hassink, 1994).

Finally, SOC in highly fertile soil may increase further in response to fertilizer application. For example, Hatch et al. (1991) reported greater accumulation of SOC under perennial ryegrass fertilized with 420 kg N/ha/yr than under perennial ryegrass/white clover.

The CCGRASS model (van den Pol-van Dasselaar and Lantinga, 1995) predicted that the rate of increase for SOC would be greatest at low to moderate rates of N (100 to 250 kg N/ha/yr). Much of the available literature supports those predictions.

## Carbon Sequestered in Pasture Soils

Pastureland soils generally have high levels of SOC and high structural stability. SOC accumulates when cultivation of arable soils ceases. For example, SOC concentration of the 0- to15-cm depth increased from ~33 to 38 g/kg during the first 5 years of pasture growth following crop cultivation in Argentina (Studdert et al., 1997). Concomitant with the increase in total C were increases in light-fraction C, soil microbial biomass, and aggregate stability. Similar improvements in aggregation and SOC concentration occurred with the conversion from annual cropping to alfalfa production during the first 5 years in Quebec, Canada (Angers, 1992).

In a longer-term study, bermudagrass, maintained for at least 35 years in south-central Texas, contained 49 MT SOC/ha in the upper 20 cm of soil. Similar soils under conventionally tilled cropping systems had only 20 to 25 MT SOC/ha (Franzluebbers et al., 1998). In another long-term study, conventionally tilled cropland was converted to either tall fescue/common bermudagrass pasture or minimum-till cropland on a Typic Kanhapludult in Georgia. After 25 years, 7.6 MT/ha more SOC had accumulated under the pasture to a depth of 20 cm than under the minimum-till cropland, which produced a summer crop and a winter cover crop with minimal soil disturbance (Fig. 12.6).

Lewis et al. (1987) reported a linear increase in SOC of 0.2 to 0.3 g/kg/yr with age of pasture by applying superphosphate and seeding legumes. In a permanent rotation trial started in 1925 and fertilized with P, Grace et al. (1995) reported a linear decline in SOC with years in fallow and years of cropping after pasture. SOC ranged from 25 g/kg under permanent pasture to 10 g/kg for the wheat–fallow rotation.

SOC generally increases following conversion of cropland to pasture, although it could take many years to reach a new steady state. Dormaar and Smoliak (1985) and McConnell and Quinn (1988) reported that it took 50 plus years for

SOC of abandoned cropland to approach the level of native rangeland. The difference in SOC to a depth of 20 cm on a Typic Kanhapludult in Georgia between tall fescue pastures established for 10 vs. ~50 years was 8.7 MT/ha (Fig. 12.7) and between Coastal bermudagrass hay land established for 10 vs. ~40 years was 2.8 MT/ha (Fig. 12.8). SOC reached a new steady state only after 200 years when arable land was allowed to revert to grass at Rothamsted (Jenkinson, 1988). Fifty percent of the change in SOC occurred in the first 25 years.

Others have reported relatively rapid SOC changes in response to land use changes. In the Great Plains, 21% (0.8 MT/ha/yr) of the C lost by decades of intensive tillage was recovered within 5 years under the Conservation Reserve Program, where cropland was converted to unharvested grasslands (Gebhart et al., 1994). In another study, 5 years of grass pasture increased SOC from 46 to 77 g/kg

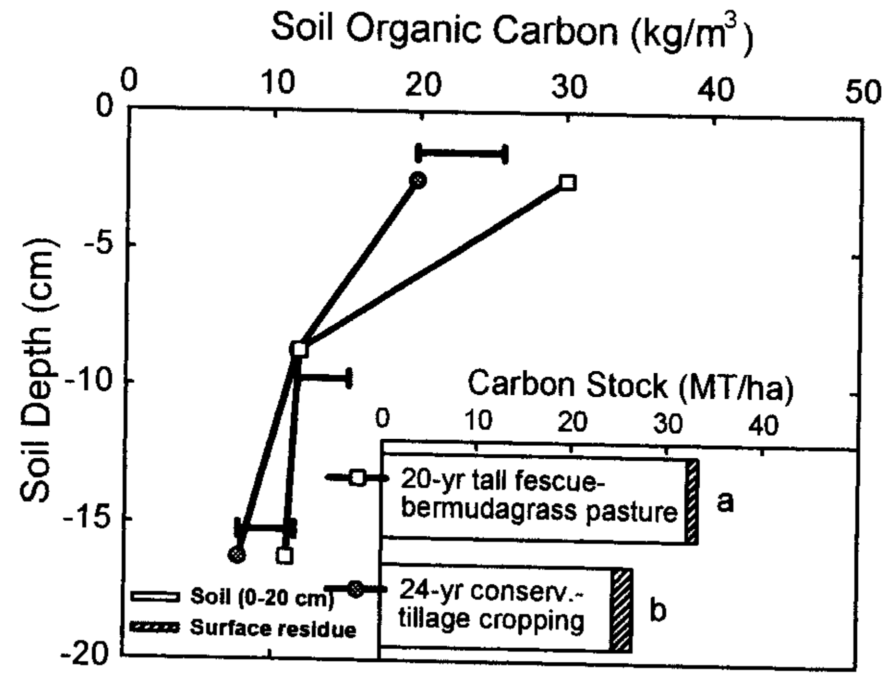



**Figure 12.6. SOC depth distribution and standing stock to a depth of 20 cm at the end of 25 years of conversion from conventionally tilled cropland to tall fescue-bermudagrass pasture or conservation tillage cropping on a Typic Kanhapludult in Georgia (Franzluebbers et al., 2000b). LSD bars are P = 0.05 within a soil depth. Horizontal bars followed by a different letter are different at P = 0.05.**

(Douglas and Goss, 1982). Richter et al. (1990) reported that 24% of SOC stored in grassland was lost in 6 years of annual tillage, mostly from a loss of root mass.

Much of the pastureland in the eastern U.S. was or could potentially support forest, because of abundant precipitation. Land use before pasture establishment could affect short- and mid-term status of SOC by altering its initial depth distribution and total quantity.

In two paired comparisons of 15-year-old bermudagrass (Tifton 44 pasture and Coastal hayland) in Georgia, SOC to a depth of 20 cm averaged 34.9 MT/ha after clearing mixed hardwood-pine forest and 29.0 MT/ha after several years of cropping (Fig. 12.9). Increases in SOC after forest clearing occurred at the soil surface, but also at a depth of 12.5 to 20 cm, perhaps due to incorporation, during the planting process, of a large pool of C-rich surface residue, which typically oc-

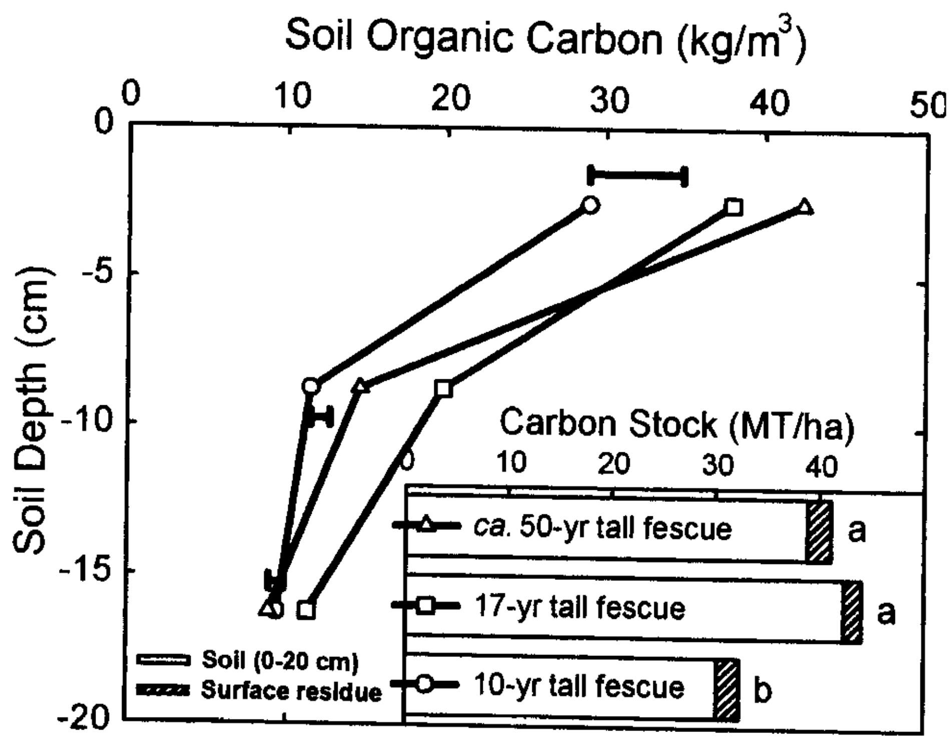



**Figure 12.7. SOC depth distribution and standing stock to a depth of 20 cm as affected by time under 'Kentucky-31' tall fescue pasture on a Typic Kanhapludult in Georgia (Franzluebbers et al., 2000b). LSD bars are P = 0.05 within a soil depth. Horizontal bars followed by a different letter are different at P = 0.05.**

curs in forest ecosystems (Fig. 12.10). This pool of surface residue in forests may be fairly recalcitrant when mixed into the soil after clearing.

## Importance of Soil Organic Carbon to Soil Quality

Pasture management, compared with crop management, typically increases SOC concentration nearest the surface (Fig. 12.11). This increase affects soil physical properties such as water infiltration. Greater rates of infiltration in turn can improve efficiency of water use and deter erosion.

Surface residues can buffer rainfall energy, thus protecting surface structure and improving infiltration. Surface residue in pastures also can be an important physical barrier to water movement across the landscape. However, removing the

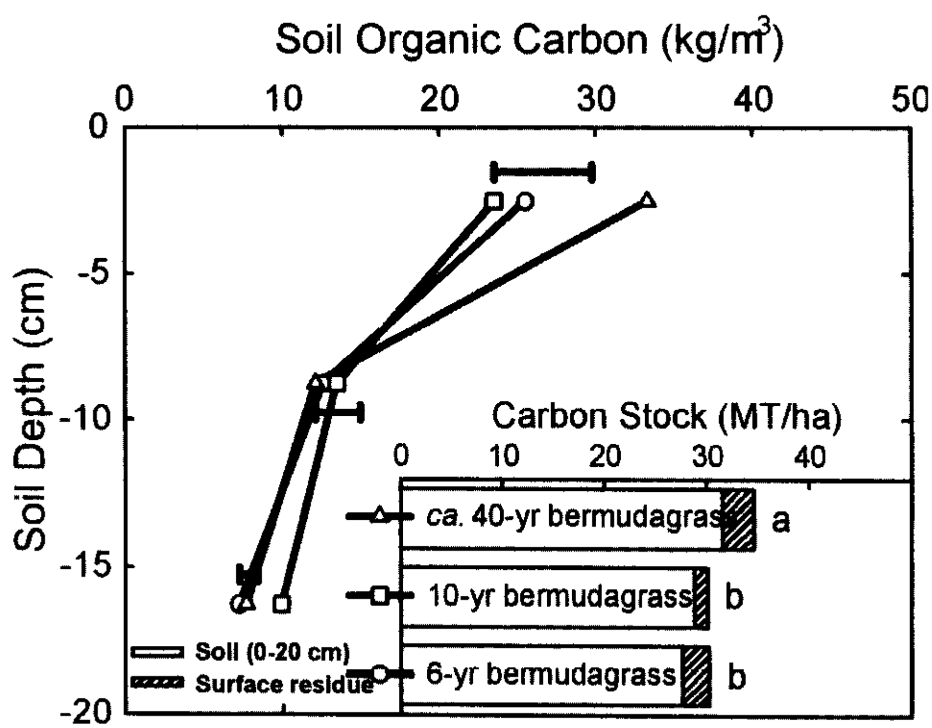



**Figure 12.8. SOC depth distribution and standing stock to a depth of 20 cm as affected by time under Coastal bermudagrass hayland on a Typic Kanhapludult in Georgia (Franzluebbers et al., 2000b). LSD bars are P = 0.05 within a soil depth. Horizontal bars followed by a different letter are different at P = 0.05.**

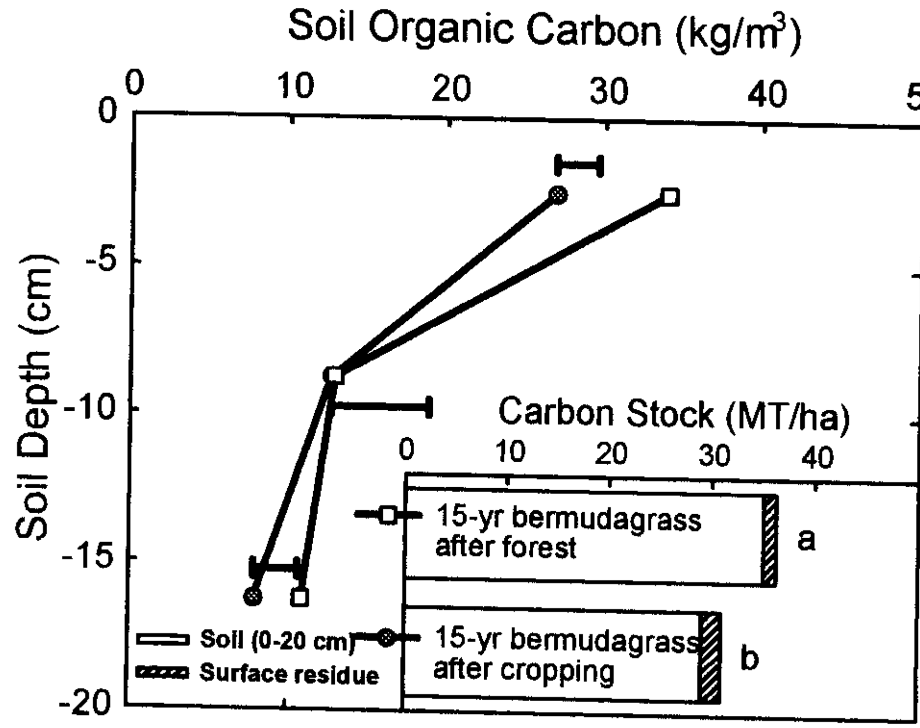



**Figure 12.9. SOC depth distribution and standing stock to a depth of 20 cm as affected by previous land use before establishment of either Coastal (hayed) or Tifton 44 (grazed) bermudagrass on a Typic Kanhapludult in Georgia (Franzluebbers et al., 2000b). LSD bars are P = 0.05 within a soil depth. Horizontal bars followed by a different letter are different at P = 0.05.**

surface residue before single-ring infiltration measurements (30-cm diameter) did not reduce steady-state water infiltration, which averaged 17 cm/hr during September in 8-year tall fescue pastures (Franzluebbers, unpublished data). These results suggest that greater infiltration rates in well managed pasture may link more closely to improvements in SOC than to accumulation of surface residue.

Despite a twofold difference in SOC in a 30-year Bavarian study, NMR & FTIR spectra of fulvic and humic acids reflected no differences in chemical stability (Capriel et al., 1992). The authors attributed differences in SOC to physical stabilization of the OM.

Soil's physical improvements with increasing SOC are known. Douglas and Goss (1982) found a linear relationship between a wet stability index and OM con-

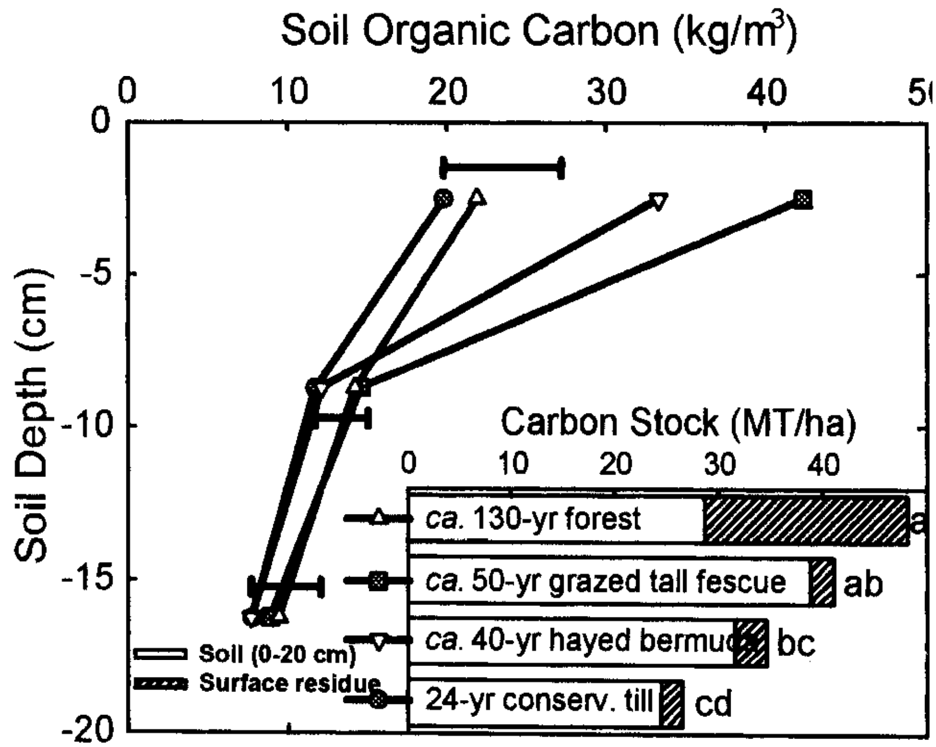



**Figure 12.10. SOC depth distribution and standing stock to a depth of 20 cm as affected by long-term management systems on a Typic Kanhapludult in Georgia (Franzluebbers et al., 2000b). LSD bars are P = 0.05 within a soil depth. Horizontal bars followed by a different letter are different at P = 0.05.**

tent. Haynes and Swift (1990) reported nearly twice as much SOC (36 vs. 20 g/kg) and more stable aggregates under 25-year-old pasture than under cropland.

The large increase in SOC near the soil surface in pasture typically leads to lower bulk density and greater porosity (Fig. 12.12), which allows water to pass through the soil surface more rapidly. The data of Carreker et al. (1977) illustrate the dependence of water infiltration on SOC concentration in the Southern Piedmont region of the U.S. Various crop/pasture rotations, compared with continuous cropping, led to increases in SOC concentration which, in turn, led to increases in the rate of water infiltration and the amount of time elapsed before runoff occurred (Fig. 12.13).

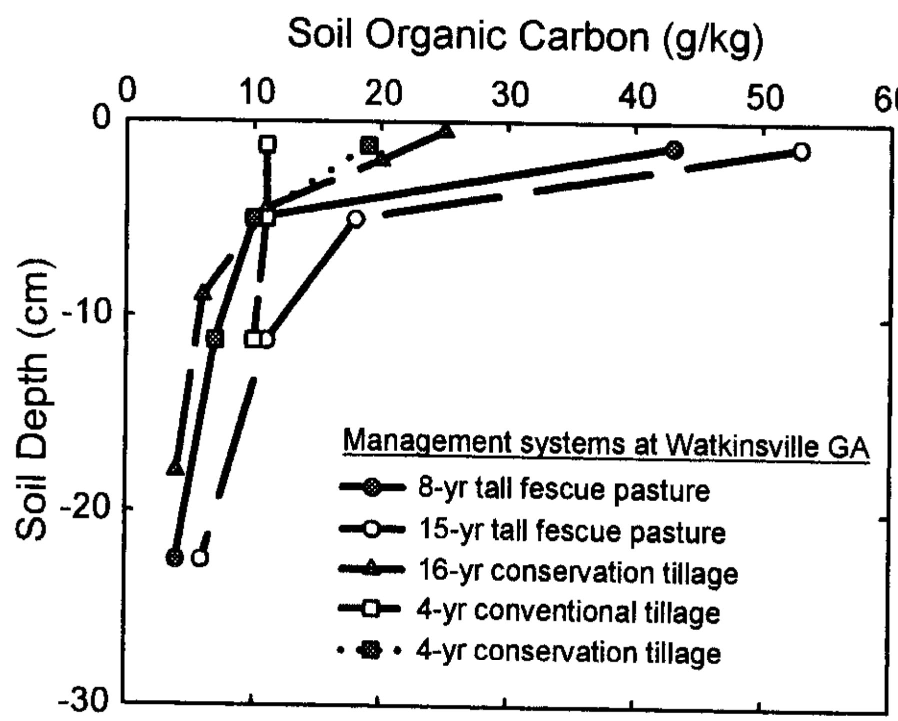



**Figure 12.11. SOC concentration with soil depth under various crop and pasture management systems on Typic Kanhapludults. Data from tall fescue pastures are from Franzluebbers et al. (1999b). Data from 16-year conservation tillage are from Bruce and Langdale (1997). Data from 4-year conservation tillage are from Franzluebbers et al. (1999a).**

## Potential Negative Environmental Consequences of Pasture Development

Sequestration of soil C can increase with increased pasture productivity and conversion of marginal cropland to pasture. In the long term, as a steady state approaches, the rate of increase will diminish, approaching zero. However, while major, positive environmental benefits will result from an increase in pasture development, negative environmental consequences also may occur. Some potential environmental costs of such a shift include water quality problems, potential C costs related to fertilization, effects of various nutrients' buildup in soils, etc.

Dairy and cow-calf industries dominate ruminant animal agriculture in the eastern U.S. Use of grasslands through grazing has always been the major source of energy and protein for cow-calf herds. Recently, a growing number of small and medium sized dairy producers have adopted grazing to provide a significant part

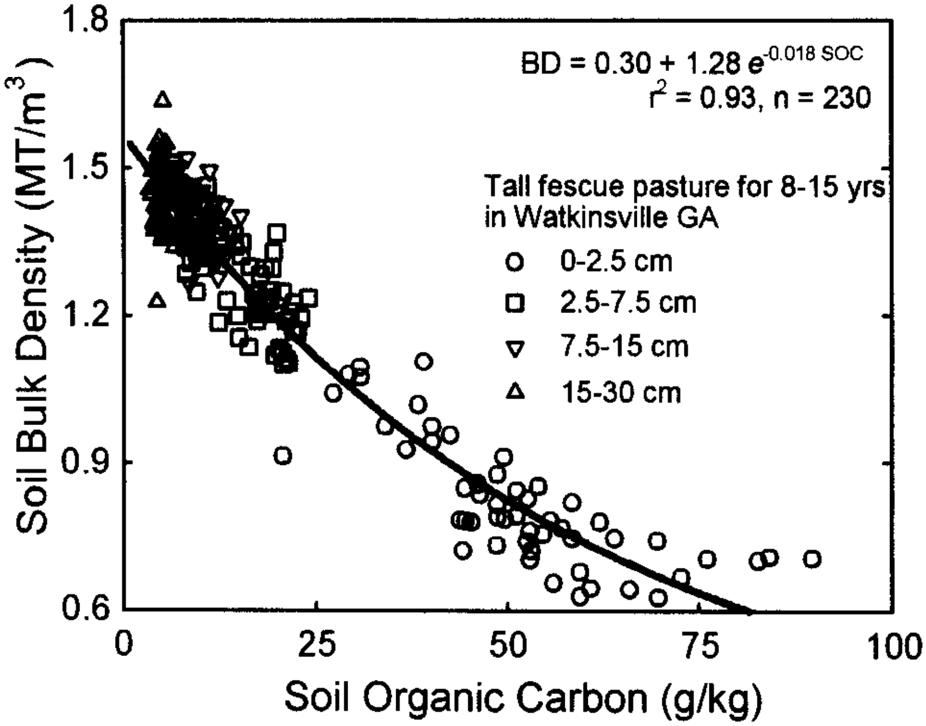



**Figure 12.12. Effect of SOC concentration on soil bulk density under tall fescue pasture. Data are from Franzluebbers et al. (1999b).**

of the energy and protein for both their milking and dry cow herds (Fales et al., 1995).

This shift has been primarily for economic reasons and has necessitated a conversion of croplands to grazing lands. The increase in soil C from this conversion also may incur environmental and economic costs. For example, water quality concerns could change from those dominated by sediment and pesticides in cropland to those dominated by fecal organisms and nutrients in pastures.

In intensively managed grazing systems adopted by dairy farmers in the northeastern U.S., animals are rotated frequently through a series of pastures during the grazing season, causing frequent defoliation of the pasture swards. The main adaptive response of plants to these episodes of defoliation is the priority allocation of C from roots to shoots and increased respiration in order to restore light interception and C assimilation through increased shoot growth. The rate of shoot growth and new leaf expansion depends on the quantity of reserve protein in the plant and the rate at which this protein is recycled within the plant.

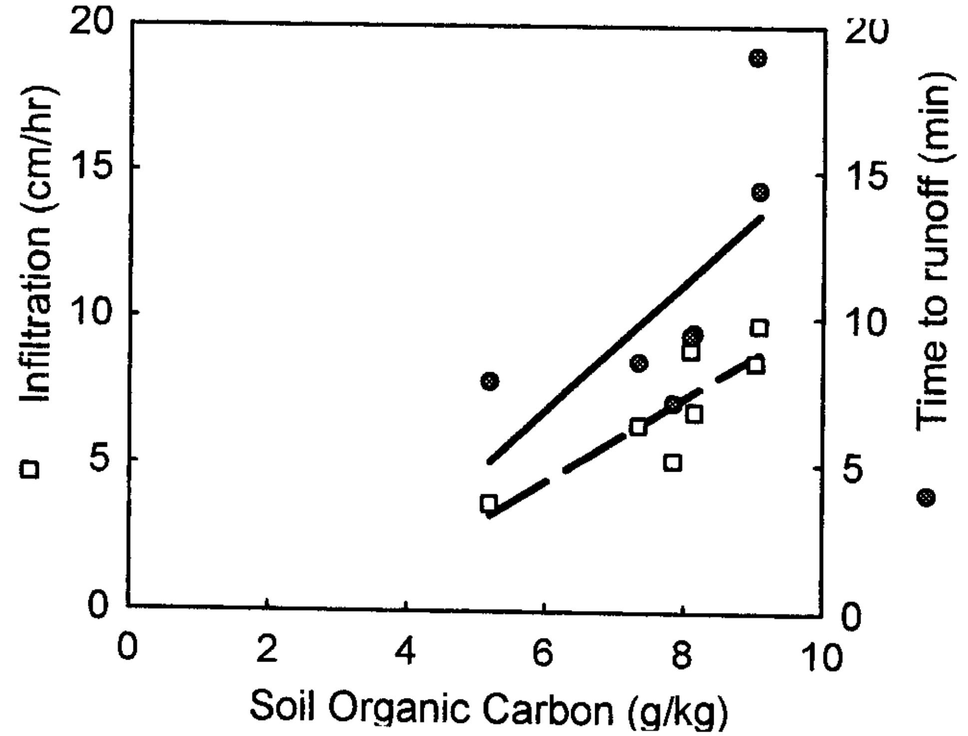



**Figure 12.13. Influence of SOC concentration on infiltration rate and time to runoff as a result of various crop/pasture rotations. Data are from Carreker et al. (1977).**

In other words, the richer a grassland system is in N, the faster it can recover from defoliation and resume sequestering C in the root system. However, the richer a grassland system is in N, the greater the threat to water quality from the leaching of urine N or applied fertilizer N (Ryden et al., 1984; Jarvis et al., 1989; Whitehead, 1995; Stout et al., 1997). Thus, there can be a trade-off between capturing $CO_2$ from the atmosphere by increasing C sequestered in the soil and improving water quality.

Legumes or fertilizer N can maintain N fertility. Legumes not only supply N to increase C sequestration and primary biomass production but also increase the quality of forage, thereby increasing production per animal. However, pasture systems driven by legume N are not as productive as those driven by fertilizer N. This means that legume systems are more profitable on a per animal basis but less profitable on a per hectare basis. If land prices were low, profits could be maximized on a per animal basis and use of legumes would be desirable. However, if land prices were high, profits would need to be maximized on a per hectare basis, and fertilizer N systems would be needed.

If fertilizer N is required to maximize profits, additional C costs are associated with manufacturing, transporting, and spreading it. Since N fertilization rates on intensively managed pastures can be higher than those on corn (Whitehead, 1995; Fales et al., 1995), the C costs of this additional N must be charged against any additional C sequestered by N-fertilized pastures. The C costs associated with mining, hauling, and grinding the lime used to neutralize the soil acidity, which N fertilization causes, also must be charged against increased soil C. There is also a direct C cost in neutralizing acid from the nitrification of ammonium nitrate or urea. As an example, 0.43 kg C could be released to the atmosphere as $CO_2$ if calcium carbonate is used to neutralize the acidity generated per kg N.

Another hidden problem associated with C sequestration by intensively managed pasturelands arises when energy and nutrient-dense feedstuffs are imported into grazing areas. Intensively grazed pastures are low in energy and high in protein relative to the needs of the grazing animal. This is especially true for the grazing dairy cow, where low intake of energy from pasture herbage can result in low milk production and high levels of urea N in milk.

Producers balance the animal's ration by supplementing the herbage with off-farm, energy-dense feed grains, much of it imported from outside the geographic region. The manure generated by feeding this grain cannot economically be returned to the fields where the grain was grown but typically remains at its destination (Lanyon, 1995). This results in a buildup of nutrients in soil (particularly P and K) on grazing dairy farms. Increased levels of P can contaminate fresh surface waters and have been associated with outbreaks of pfisteria. High levels of soil K cause concerns because high levels of K in pasture herbage have a deleterious effect on the health of grazing animals, especially dry cows.

## Conclusion

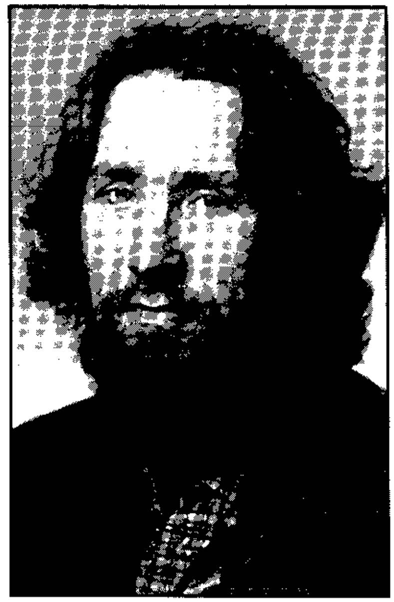
Our review of SOC status and dynamics suggests we can store more C in the grazing land soils of the eastern U.S. (Table 12.4). The magnitude and duration of this storage is difficult to estimate for the region. Converting marginal cropland to pasturelands will increase SOC. Changes in how animals, plants, and soils are managed also can affect the balance between C inputs to the soil via plant fixation and losses of SOC to the atmosphere via decomposition.

Where pasturelands are highly productive and SOC is already high, small or no increases in C storage can be expected. Larger increases may be made on marginally productive pasturelands by improving soil fertility or managing animals and plants better. Making pastures more productive, however, could compromise efforts to improve water quality and could decrease farm profitability.

**Table 12.4. The effects of pasture management methods on C storage in soil.**

| Factor | Measured Effect on NPP or Forage Quality | Measured or Inferred Effect on C Storage in Soil |
|---|---|---|
| **ANIMAL MANAGEMENT** | | |
| Grazing grasslands | More C returned to soil for rapid incorporation. | Increase SOC. |
| Intensive grazing | With adequate moisture, intensive management increases NPP. Increased foot traffic breaks down residue. | Increase SOC. |
| | With limited moisture, increased stocking can damage stands. | Decrease SOC. |
| **FORAGE MANAGEMENT** | | |
| Replacing $C_3$ grasses with $C_4$ grasses | At low to moderate fertility, increase NPP and reduce forage quality. | Increase SOC. |
| | At high fertility, little change in NPP. | Little change in SOC. May not be sustainable. |
| Replace endophyte infected fescue with uninfected fescue | Increase forage quality. | Decrease SOC. |
| Increase harvest frequency | Reduce NPP, increase forage quality. | Decrease SOC. |
| Delay harvest or grazing | Reduce forage quality. | Increase SOC. |
| **SOIL MANAGEMENT** | | |
| Liming | Increases P availability and NPP. | Increases SOC. |
| P fertilization | If P deficient, increase NPP. | Increase SOC. |
| | If P is adequate or in excess, no change. | No change. |
| N fertilization | Low inherent fertility, increase NPP and forage quality. | Increase SOC. |
| | High inherent fertility; NPP, and decomposition of SOC, no change or increase. | No change, decrease, or increase in SOC, depending on relative change in NPP and decomposition. |
| Manuring | Increases NPP if fertility limits growth. | Increases SOC. |
| Drainage | Increases NPP, increases SOC decomposition. | Decreases SOC. |

## In Memory of Ron Schnabel



Dr. Ronald R. Schnabel died on February 21, 2000, in State College, PA. Ron was born on March 19, 1951, in Eureka, SD. He was the son of Ruth Ketterling Schnabel and the late Gottfried Schnabel.

Ron graduated from South Dakota State University in March 1974 with a B.S. in Environmental Management and in 1977 with a M.S. in Soil Science. He received his Ph.D. in Soil Science from Washington State University in 1981. His Ph.D. research was innovative and forward-looking. He successfully applied soil physics and soil chemistry to the modeling of nitrate leaching and denitrification losses from furrow irrigated soils.

Ron joined the Agricultural Research Service at University Park, Pa., in 1980 as a Soil Chemist. He was a research scientist and project leader at the Northeast Watershed Research Center and then at the Pasture Systems and Watershed Management Research Laboratory. He was extremely productive and was best known for developing innovative field-based methodologies to measure inorganic N losses, and for his stream riparian zone work. He developed methods for sampling and estimating nitrate and ammonium leaching in soil, using ion exchange resins, and for determining gas diffusivities in soils, especially nitrous oxides. He showed that stream riparian zones and floodplains in northeastern hill land watersheds could intercept and denitrify excess nitrate en route to streams, but he also cautioned us with work that showed this beneficial site-specific effect could be much reduced at the watershed scale. Prior to his untimely death, Ron had expanded his research to look at carbon sources and carbon-N dynamics affecting N availability and losses from stream riparian zones and heavily manured soils. He also had expanded his riparian zone management work to include the impact on benthic organisms.

Ron was a gifted and giving scientist who made a difference. He worked very effectively with others and very much enjoyed working with undergraduate and graduate students. In addition to his professional activities, Ron served his community as a volunteer instructor at the Mid-State Literacy Council. In this capacity he taught reading, writing, math, and life skills. His fellow scientists, collaborators, co-workers, and friends will sorely miss him.

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